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Theory of Mechanoluminescence Produced During Cleavage of Elemantal and III-V Semiconductors

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ABSTRACT

The present paper reports that the formation of crack-induced localized state is responsible for the Mechano luminescence (ML) produced during the cleavage of elemental and III-V semiconductors. When an elemental and III-V semiconductor is cleaved, initially the ML intensity increases with time and attains a peak value I_m at the time tm corresponding to completion of the cleavage of the semiconductor and then it decreases following power law decay. Both I_m and I_T increases linearly with the area of newly created surfaces of the crystals. From the measurements of the ML intensity, the velocity of crack propagation in material can be determined by using the relation $v=H/t_m$.

Keywords: Mechano luminescence intensity and newly surfaces.

INTRODUCTION

Mechanoluminescence (ML) is a type of luminescence produced during mechanical deformation of solids. It can be excited either by grinding, rubbing, cutting, cleaving, shaking, scratching, compressing or by crushing of solids. ML can also be excited by thermal shocks caused by drastic cooling or heating of materials or by the shocks –waves produced during exposure of sample to powerful laser pulses. ML also occurs during separation of two dissimilar materials in contact[1-5]. The present paper reports the theory of mechano-luminescence produced during the cleavage of elemental and III-V group semiconductor and make a comparison between the experimental and theoretical results.

THEORY

As the atom drawn from away from each other in an advancing crack tip, the decreasing wave-function overlap across the crack may results in localized states. Anderson localization is expected to results from variations in crack width and from

mismatch across the cracks due to shear displacements[6]. Decreasing wave –function overlap is generally associated with increasing electron energy. If the energy of these localized states approaches that of the conduction band, transition of electrons to the conduction band via tunneling would be conduction band , energy due to high stress fields near the crack tip. Subsequently, the radiative recombination of electrons and holes may rise to ML.

The total number of photons produced during the electron of unit surface area are $3x10^8$, $1.52x10^{10}$,$7x10^6$ and $3x10^4$ for Ge ,Si, InP and GaAs semiconductors, respectively[5]. The band gaps of Ge, Si, InP and GaAs are 0.67,1.14,1.35 and1.43 eV respectively. Except Ge, it follows that the number of photons emitted decreases with increasing energy of the band gap. This facts supports the ML model involving formation of crack induced localized states. The low value of Ml efficiency in Ge as compared to that in Si may probably be due to the low value of the efficiency of radiative transition in this crystal.

Strube and Linke[7] have measured the time-resolved crack velocity during the cleavage of alkali halide crystals. They shown that initially the crack moves at low velocity, but very soon it attains affixed velocity after attaining a certain length .If a crystal having length L, breadth W and thickness H is cleaved along the plane parallel to the breadth side, the rate of creation of new surfaces is given by 2Wv, where v is the average velocity of the separation of cleavage plane or, in other words, the velocity of crack propagation. If B is the number of free charge carriers produced during the creation of unit surface area, then the rate of the change carriers may be expressed as

$$g=2BWv \qquad (1)$$

In intrinsic semiconductors the number of electrons is equal to number of holes. In this case , luminescence is produced during the radiative recombination of holes and electrons. If α_1 and α_2 are the recombination coefficient for radiative and non-radiative transitions, then the rate equation may be written as

$$\frac{dn}{dt} = g - \alpha n^2 \qquad (2)$$

Where $\alpha = (\alpha_1 + \alpha_2)$, and n is the number of carriers in the respective band at any time t.

For n=0, at t=0, the integration of equation (2) gives

$$n = \sqrt{g/a}\tanh^2 t\sqrt{ga} \qquad (3)$$

Case-I Rise of ML intensity

The rise of intensity of bimolecular ML may be given as

$$I_r = an^2 = \frac{a_1 g}{a}\sqrt{g/a}\tanh^2 t\sqrt{ga} \qquad (4)$$

For small value of t, eq.(4) may be written as

$$I_r = a_1 g t^2 n^2 \qquad (5)$$

Equation (5) indicates that I_r should increases quadratically with t.

Equation (4) shows that when a semiconductor material is cleaved, initially, the ML intensity should increase quadratically with time t and finally it

should attain a saturation value I_{rs} given by the equation

$$I_{rs} = \frac{2a_1}{a_1 + a_2} BWv \quad (6)$$

Case-II Decay of ML intensity

When the light source will be switch off, the rate of generation, g of carriers will become zero and eq. (2) may be expressed as

$$\frac{dn}{dt} = -an^2 \quad (7)$$

If the cleavage is completed at $t=t_m$ then taking $n = \sqrt{g/a}$ at $t=t_m$ and we get

$$n = \sqrt{g/a}\,\frac{1}{(\sqrt{ga})(t-t_m)+1} \quad (8)$$

Thus, the decay of ML intensity may be given by

$$I_d = a_1 n^2 = \frac{a_1 g}{a}\,\frac{1}{[(\sqrt{ga})(t-t_m)+1]^2} \quad (9)$$

For $(\sqrt{ga})(t-t_m) > 1$ we get

$$I_d = \frac{a_1}{a^2}\,\frac{1}{(t-t_m)^2} \quad (10)$$

The above equation shows that the decay of ML intensity should follow the power law.
For $t=t_m$ and using eq.(9), the maximum ML intensity may be expressed as

$$I_m = \frac{a_1 g}{a} = \frac{2a_1 BWv}{a} \quad (11)$$

From eq. (11) we get

$$\frac{I_m}{I_m} = [(\sqrt{ga})(t-t_m)+1]^2$$

or

$$[\sqrt{\frac{I_m}{I_m} - 1}] = [(\sqrt{2BWva})(t-t_m) \quad (12)$$

Equation (12) indicates that the plot between $[\sqrt{\frac{I_m}{I_m} - 1}]$ and $(t-t_m)$ should be a straight line, in which the slope should be equal $\sqrt{2BWva}$

Total ML Intensity

The total ML intensity may be given by the area below the ML intensity versus time curve, and it may be express as

$$I_T = \int_0^{t_m} \frac{a_1 g}{a} \tanh^2 t\sqrt{ga}\,dt + \int_{t_c}^{\infty} \frac{a_1 g}{a}\,\frac{1}{[(\sqrt{ga})(t-t_c)+1]^2} \quad (13)$$

Integrating eq.(13), we get

$$I_T = \frac{a_1 g^{1/2}}{a^{3/2}}[t_m\sqrt{ga} - \tanh t_m\sqrt{ga} + 1 \quad (14)$$

For $t_m\sqrt{ga} > 1$, $\tanh t_m\sqrt{ga} = 1$ thus eq. (14) may be express as

$$I_T = \frac{a_1 g}{a} t_m = \frac{a_1 BA}{a} \quad (15)$$

Where A is the area of newly created surfaces.

EXPERIMENTAL SUPPORT TO THE PROPOSED THEORY

Fig.1 shows the ML intensity versus time plot obtained during cleavage of InP crystals. From the results reported by Haneman and Mc Alpine[2] and Li *et al*.[3-5], it is evident that the rise of ML follows the quadratic relation between I_r and t, but for some smaller crystals this is not apparent. During the fracture of Si crystals, Langford *et al*.[6] have found anon linear increase of the current with time.

Fig. 2 shows the plot $[\sqrt{\frac{I_m}{I_m}} - 1]$ versus (t-t_m) curve for Si,Ge,$Ge_{0.2}$,$Si_{0.8}$,InP and GaAs crystals cleaved in vacuum. It is evident that this plot is a straight line with a positive slope, which support eq.(12)

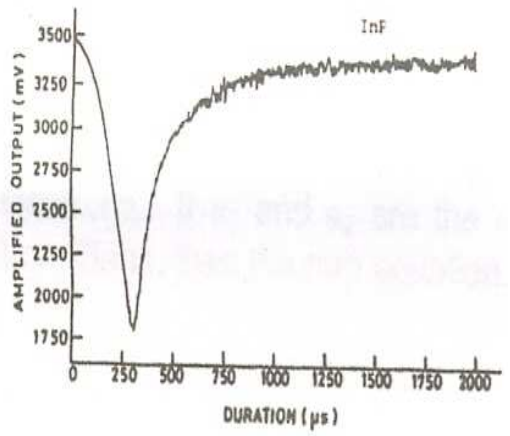

Fig. 1 luminescence signal from InP 15 mm wide by .74 mm thick, observed on P detector through 1.32 -1.45eV filter Cleaved in vacuum of $5x10^{-5}$ torr (after Le *et al*.[5]

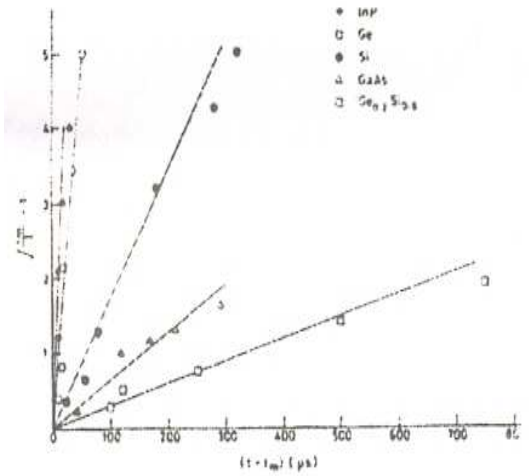

Fig. 2 plot $\sqrt{\frac{I_m}{I_d} - 1}$ versus (t - tm) curve for Si, Ge, $Ge_{0.2}$, $Si_{0.8}$, InP and GaAs crystals cleaved in vaccume .

CONCLUSION

The mechanism related to the formation of crack –induced localized states is responsible for the for the mechano-luminescence excitation produced during the cleavage of elemental and III-V semiconductors. From the measurement of the ML intensity, the velocity of crack propagation in a material can be determine by using the relation $v=H/t_m$.

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